consistent across different test methods and are also in good agreement with the results obtained by others. A summary of engineering properties of Sydney Hawkesbury sandstone is given in Table 4.

Table 4. Engineering properties of Sydney Hawkesbury sandstone

Parameters	Test methods	Moisture condition	Range of values	Average value
q_u	uniaxial	high humidity room	8.7 ~ 23.1 (MPa)	16.9 (MPa)
		air dried	25.1 ~ 35.6 (MPa)	30.1 (MPa)
		oven dried	38.1 ~ 46.2 (MPa)	41.3 (MPa)
E	uniaxial	high humidity room	2.18 ~ 6.45 (GPa)	4.50 (GPa)
		air dried	5.30 ~ 8.60 (GPa)	6.79 (GPa)
		oven dried	7.40 ~ 10.2 (GPa)	8.42 (GPa)
ν	triaxial	saturated	0.09 ~ 0.10	0.10
$\phi_{(intact)}$	triaxial	saturated	48.5 ~ 50.0 (deg)	50.0 (deg)
	direct shear	high humidity room	51.0 (deg)	
$c_{(intact)}$	triaxial	saturated	2.2 ~ 2.4 (MPa)	2.3 (MPa)
	direct shear	high humidity room	2.35 (MPa)	
$\phi_{(sliding)}$	direct shear	high humidity room	31.0 ~ 33.0 (deg)	32.0 (deg)

The moisture content of sandstone has a significant influence on the strength of sandstone. As can be seen from Figures 3 and 4, the strength of sandstone reduces as the moisture content increases.

ACKNOWLEDGEMENT

The first author gratefully acknowledges the financial support provided by the Australian Research Council and Monash University.

REFERENCES

Australian Rock Engineering Consultants ARENCO (1973). Progress report - foundation investigation proposed MLC centre, Sydney

Chiu H.K. Johnston I.W. and Donald I.B. (1983) Appropriate techniques for triaxial testing of saturated soft rock. *Int. J. Rock Mech. Min. Sci. and Geom. Abstrs*, Vol. 20, No. 3, pp 107 – 120.

Gu X.F (2001). Shear behaviour of sandstone-concrete joints and pile shafts in sandstone. PhD Dissertation Dept. of Civil Engng., Monash University.

Gu X.F, Seidel J. P and Haberfield C.M (2003). Direct shear tests of sandstone-concrete joints. *International Journal of Geomechanics*, Volume 3, Number ½, ASCE, pp 21 – 33.

Lam T.S.K. (1983) Shear behaviour of concrete-rock joints. PhD Dissertation. Dept. of Civil Engng., Monash University.

Ooi L.H. (1989) The interface behaviour of socketed piles. PhD Dissertation. School of Civil and Mining Engineering, the University of Sydney.

Pells P.J.N. (1977). Measurement of Engineering Properties of Hawkesbury Sandstone. *Australian Geomechanics Joural*, Vol. G5, No.1 pp. 10-20.

Standard (1969) "Hawkesbury Sandstone" in *Geology of New South Wales*, G.H. Packham. (ed). Geol. Soc. of Australia, Sydney, pp. 407-415.

EUROCK 2004 & 53rd Geomechanics Colloquium. Schubert (ed.) © 2004 VGE

Time-Dependent Behaviour of Gypsum and Anhydrite Rocks: Preliminary Results

Mauricio Giambastiani
Graduate Student, São Carlos Engineering School – University of São Paulo (Brazil)

Tarcísio B. Celestino
Professor, São Carlos Engineering School – University of São Paulo & Themag Engenharia (Brazil)

Antonio Airton Bortolucci
Professor, São Carlos Engineering School – University of São Paulo (Brazil)

ABSTRACT: Anhydrite and gypsum rock masses present time dependent deformations under the actions imposed by engineering works. This behavior is usually attributed, in the scarce literature available, only to the expansion process due to hydration and transformation of anhydrite into gypsum. There are no definite proofs in favor of this theory and it is questioned by some authors. The study of rheological properties, in both viscoelastic and viscoplastic fields, may bring some light to explain those deformations. Preliminary results of an experimental program including long-term unconfined compression tests and axial free swelling tests on gypsum and anhydrite samples from Brazil and Argentina are presented. The results indicate that the elastoviscoplastic behavior of these rocks is significant to be considered with respect to the stress increase imposed by some engineering works. Nonetheless the theory of expansion due to hydration must be considered as well.

1 INTRODUCTION

Evaporitic rocks present some geomechanical peculiar behavior which has called the attention of researchers from several areas. Abundant studies on salt rock are an example. In spite of broad knowledge about salt rock, there is only rare and sparse information in the literature about the geomechanical behavior of sulfate evaporitic rocks like anhydrite and gypsum. The literature contains information about some ancient underground works located in the Alps, which presented long term deformations, large enough to cause significant damage to the reinforced concrete (Steiner, 1993; Sahores, 1963; Henke, 1976; Grob, 1976; Krause, 1976).

Several authors explain this phenomenon based on the theory of anhydrite hydration ($CaSO_4$) transforming it into gypsum ($CaSO_4.2H_2O$).

This mineralogical process may involve volume increase of the order of 60%. This theory colides with two important facts. First, a set of important underground works excavated in this type of rock did not present swelling under that level of deformation (Sahores, 1962). Second, geological evidences of the mineralogical transformation do not show the occurrence of such volume increase (Orti Cabo and Rosell Ortiz, 1981; Carozzi, 1993).

Facing a theory without definite proofs, the study of rheological properties of these rocks will offer another point of view. This was the motivation for the research reported here, encompassing all the stages of geomechanical characterization of these rocks, ranging from conventional short duration to long term tests (creep under uniaxial compression and free swelling). In the following items, relevant preliminary results of these tests will be presented.

2 MATERIALS AND METHODS

Samples of anhydrite and gypsum from the Auquilco Formation of lower Jurassic age from Mendoza, Argentina (Auquilco anhydrite, alabastro gypsum, laminar gyosum and massive gypsum) were colected from the Principal Andean Cordillera. Gypsum from the Santana Formation of lower Cretaceous age, Araripe Basin, from Pernambuco, Brazil (nodular and banded gypsum) and anhydrite from the Muribeca of Aptian age from Sergipe, Brasil where also colected. Petrographic analyses, determination of index properties and short duration tests (Brazilian, uniaxial compression and triaxial compression tests) were carried out according to ISRM Suggested Methods. The latter were performed in a servo-controlled testing machine MTS 815 from the Rock Mechanics Laboratory, São Carlos Engineering School, University of São Paulo. For the free expansion tests, the method suggested by ISRM was adopted. The creep tests were performed according to the experimental standards proposed by ASTM (D4405-93).

3 GEOTECHNICAL PROPERTIES

Table1. Main geotechnical characteristics of the rocks studied.

Table 1. Geotechnical properties

Rock	Tensile Strength MPa	Uniaxial Strength MPa	Defor. Modulus GPa	Poisson Ratio
Alabastro Gypsum	0,5 ± 0,1	4,8 ± 1	3,3 ± 1,27	0,3 ± 0,26
Massive Gypsum	4,5 ± 1	25,19 ± 6,1	19,67 ± 0,9	0,21 ± 0,01
Laminar Gypsum	3,5 ± 0,9	44,7 ± 9,9	32,5 ± 12,3	0,26 ± 0,18
Banded Gypsum	2,9 ± 0,2	24,3 ± 0,6	30,67 ± 4,5	0,2 ± 0,04
Nodular Gypsum	3,4 ± 0,5	40 ± 4,5	36,7 ± 5,2	0,21 ± 0,02
Auquilco Anhydrite	6,8 ± 2,5	102 ± 11,2	69,2 ± 2,3	0,27 ± 0,03

4 TIME DEPENDENT BEHAVIOR

4.1 *Free Axial Swelling Tests*

In this research, five axial swelling test were carried out on Auquilco anhydrite samples and four on gypsum. The tests consisted of measuring axial displacement of specimens submerged in a water solution of calcium sulphate. Figure 1 shows the results of those tests. The first tests on anhydrite (curves 1 and 2) and gypsum (curves 7, 8 and 9) were carried out by initially distilled water, and then satured solution, in order to investigate the effect of concentration on the swelling process.

It can be clearly observed that anhydrite samples (curves 1 to 5) and gypsum samples with high anhydrite content (curve 10) show linear increase of the axial strain and gypsum samples with low anhydrite content show volume decrease, probably due to gypsum solution. Anhydrite swelling shows a linear trend with time and strain rates vary between 0.6 and 1.1% per year. Macroscopic observations of specimens after tests show whitish surface and the formation of gypsum acicular crystals forming a continuous layer. Microscopic observations are not available as yet with respect to the reaction interface. It is possible that anhydrite specimen swelling is due in large amount to the volume increase from this external gypsum layer, and not to generalizated transformation of the anhydrite matrix. The transformation seems to occur only in a thin external layer responsible for the whitish color at the surface. On the other hand, gypsum specimens did not show this external gypsum layer, and the volume decrease may be a consequence of gypsum and carbonate solution.

4.2 *Creep test under constant stress uniaxial compression*

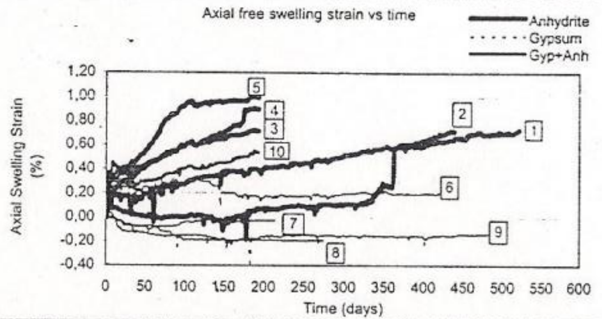

Figure 1. Axial free swelling strain vs time for anhydrite and gypsum

Creep tests under constant stress uniaxial compression are underway in order to characterize the stress-strain-time behavior in a column-type frame which allows five test to be carried out simultaneously. The frame, the loading system and the data acquisition system are installed in a controlled temperature and humidity room (18°C ±1°C and 37% ± 5% relative humidity). The test consist of three loading and unloading cycles with duration of 22 and 7 days respectively. The applied loads correspond to stress ranging from 25% to 80% of the unconfined compressive strength. Viscoelastic and viscoplastic parameters were evaluated for the primary and secondary creep condititons. Burger's rheological model was adopted and the constants were obtained by curve adjustment to the data. The curves of axial and radial strain versus time for banded and nodular gypsum and Auquilco and Muribeca anhydrites are shown in Figure 2.
According to Burger's model, axial strain rate is given by:

$$\dot{\varepsilon} = \frac{2\sigma_1}{9K} \div \frac{\sigma_1}{3G_1} + \frac{\sigma_1}{3G_1} - \frac{\sigma_1}{3G_1} e^{\frac{-G_1 t}{\eta_1}} + \frac{\sigma_1}{3\eta_2} t \qquad (3)$$

where K is the time-independent bulk modulus, G_1 and G_2 the shear moduli of delayed and instantaneous responses respectively, η_1 and η_2 are viscosity components controlling primary and secondary creep. Curve adjustement by the least square technique yielded the values shown in Table 2 for different stress levels.

For Muribeca anhydrite, G_1 varies from 57 GPa for stress level corresponding to $0.4\sigma_c$ to 334 GPa for $0.8\sigma_c$, indicating that the component of delayed elastic strain decreases with the intensity of applied stress; η_1 varies between 130 and 230 GPa.day forthe same stress level; G_2 is roughly constant, varying in the range of 23 to 29 GPa ; η_2 increases linearly with the stress level. Strain rates ranged between $6.05\text{x}10^{-5}$days^{-1} ($7\text{x}10^{-10}$s^{-1}) and $8.64\text{x}10^{-4}$days^{-1} ($1\text{x}10^{-3}$s^{-1}). For stress lower than 20MPa viscous flow is not apparently observed. Plastic strains, as observed in Figure 2, increase with time, and viscoelastic strains keep constant, about 10% of total strain.

Auquilco anhydrite presents time-dependent strain components less significant than Muribeca anhydrite. The former has higher strength and lower deformability. Strain rates vary in the range of $8.6\text{x}10^{-5}$days^{-1} ($1\text{x}10^{-9}$s^{-1}) and $8.6\text{x}10^{-6}$days^{-1} ($1\text{x}10^{-10}$s^{-1}) and total viscoelastic strain in the range of 1% to 11%, with an average of 3%. Plastic strains are not much significant and are in the range of 7% (Figure 2). Other important aspect is the fact that it does not present viscous behaviour for stresses higher than 25MPa ($0.3\sigma_c$). The difference in geomechanical properties presented by two types of anhydrite is due to different geological and deformation histories. Auquilco anhydrite was subjected more severe tectonic processes stiffening the material. Gypsum presents strain-time curves with well defined primary creep and secondary creep presents low rate. Strain rates for both types of gypsum ranges between $1.7\text{x}10^{-4}$days^{-1} ($2\text{x}10^{-9}$s^{-1}) and

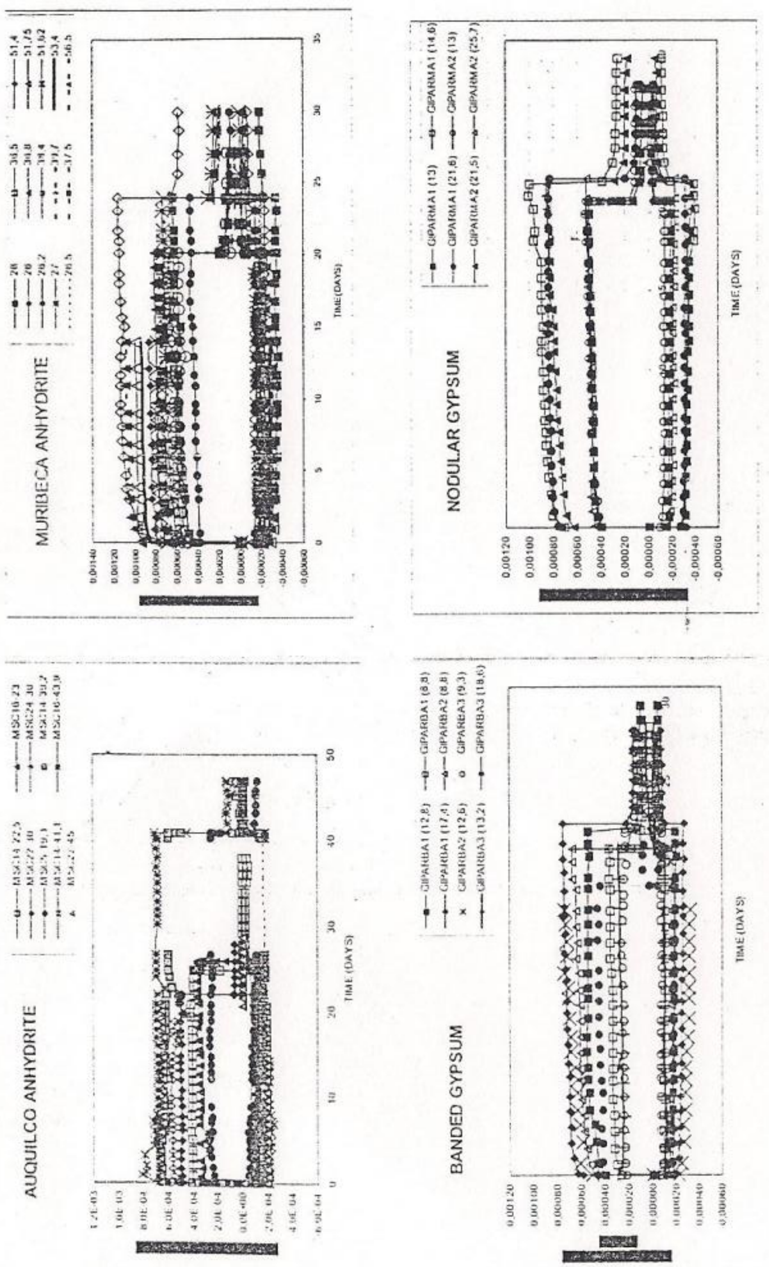

Figure 2. Deformation – time curves of the anhydrite and gypsum

$1.7x10^{-3}days^{-1}$ ($2x10^{-8}s^{-1}$). The ternary diagram of Figure 3, modified from Özgenoğlu (1998), shows that the viscoelastic strain component ranges between 5% and 20% for banded gypsum and between 8% and 17% for nodular gypsum.

Table 2. Burger's Model Parameter

ROCK	STRESS (MPa)	K (MPa)	G1 (MPa.dia)	G2 (MPa)	v1(MPa.dia)	v2 (MPa.dia)
Banded Gypsum	8.8	25620	73659	14490	73746	1437871
	8.8	12380	32737	9169	29195	950433
	12.8	53585	60858	9122	20286	442965
	13.2	48176	1140773	23733	204440	1958975
	17.3	25630	72244	12573	72244	1870391
	18.7	48403	103664	18604	2494329	8219835
Nodular Gypsum	13.0	37016	86967	13521	54124	1721224
	13.0	19636	72489	17237	136772	1401077
	14.8	26419	49272	8229	17939	673682
	21.5	61421	79506	12955	75458	1064252
	22.0	59404	81515	11223	75063	8560482
	25.7	50143	214360	27134	27072	3366860
Auquilco Anhydrite	19.29	48906	160777	48558	167335	0
	22.48	37561	1106938	29065	356037	0
	23.06	44690		34112		10631627
	27.07	52454	300739	40039	558734	90221559
	30.22	31379	251817	31876	158376	100726911
	30.88	49603	514636	34120	289658	26306262
	49.27	50640	234619	40919	1160389	163416252
Muribeca Anhydrite	26.14	56882	22933	30224	1963829	0
	26.2	66692	79424	24090	236389	2334260
	26.60	42224	68209	22620	107959	2661637
	27.21	42982	90692	21323	148231	2933215
	36.73	41424	138237	23870	330025	14024694
	37.96	44010	180757	27973	252372	4149603
	38.40	58044	213313	34458	391458	51240302
	39.69	52714	189017	27933	349940	18990103
	51.38	62279	342533	28513	12738317	178039281
	51.75	46943	575049	24716	258561	12577518
	53.37	53823	296476	29072	287472	9006868

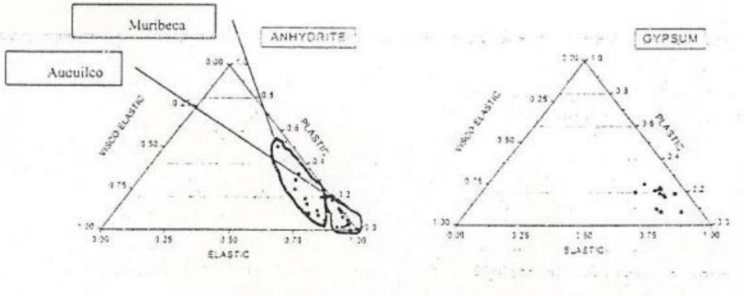

Figure 3. Ternary diagrams for anhydrite and gypsum

Plastic strain components are in the range of 17% to 23% for the banded variety and 8% to 25% for the nodular one. Both types of rock do not seem to present a threshold stress level for the onset of creep.

It was observed by direct and indirect means that the initiation crack propagation is the mechanism responsible for creep strain. It is plausible to state that a constitutive model based on the theory of progressive damage will be adequate to predict stress-strain-time behaviour of this type of rock.

5 FINAL REMARKS

1- The process of transformation of anhydrite into gypsum is still not clear, and depends, in real scale, on several factors which cannot be fully reproduced in laboratory. Anhydrite samples studied present volume increase by surface deposition of gypsum crystal by mineralogical conversion. Experimental results show that the formation of this gypsum layer only occurs for anhydrite and not for gypsum. Strain rates range between 0.6% to 1.1% per year. For a 10-m diameter tunnel and swelling zone of 2 m around the tunnel, convergence would be in the range of 1 to 2 cm per year. These values are in the range of what has been reported by Steiner (1993) for the Hauenstein Summit tunnel (>10mm/year) and Wagenburg Tunnel (7mm/year).

2- Creep tests indicate that gypsum, as expected, present higher viscoelastic and viscoplastic strains than anhydrites. Strain rates during secondary creep are roughly 10 times larger for gypsum as compared to anhydrite. Strain rates for Muribeca anhydrite (10^{-8} to $10^{-10}s^{-1}$) are larger than these for Auquilco anhydrite (10^{-9} to $10^{-10}s^{-1}$). This difference can be attributed to the higher level of stress history to which the latter has been subjected. Considering free swelling rates for Auquilco anhydrite and the same conditions for the hypothetical tunnel, convergence rate in the range of 0.6 to 6 cm per year could be expected.

3- Comments of item 2 and 3 show that free swelling and creep strain are of the same order of magnitude. The large strains observed in tunnels can be attributed to them, ocurring isolately or in combination.

4- Rheological models are a simple form to obtain deformation parameters. However they fail for generalized conditions like 3-dimensional stress field. Some of them, like Burger's model, fails even for nonlinear behaviour under uniaxial stress. Future analyses should focus on the microcracks propagation phenomenon for the proposition of a constitutive model based on physical mechanism.

5- Since both creep and transformation of anhydrite into gypsum are phenomena that can occur simultaneously in nature, it seem to be appropriated to study experimentally coupled effects between the two processes.

ACKNOWLEDGMENTS

This research was carried out under financial support by FAPESP – the research funding agency for the State of São Paulo under contract 02/00630-0. CAPES and CNPq – agencies from the Federal Government of Brazil, also contributed for this work. PETROBRAS kindly supplied Muribeca anhydrite samples. IPT – Institute for Technological Research from the State os São Paulo – contributed with part of the long term testing equipment. The authors are grateful to these institution.

REFERENCES

American Society for Testing and Materials 1993 - ASTM D 4405 – 93. Standard Test Method for Creep of Cylindrical Soft-Rock Core Specimens in Uniaxial Compression (CD ROM).

Carozzi, A. 1993. Sedimentary Petrography. Prentice Hall, 263 p.

Grob.H. 1976. Swelling and heave in Swiss Tunnels. Bull. Intern. Assoc. Eng. Geol. V13: 55-60.

Henke, K.F. 1976. Magnitude and rate of heave in tunnels in calcium sulphate bearing rocks. Bull. Int. Assoc. Eng. Geol. 13: 61-64.

Krause, H. 1976. Sulphate rocks in Baden-Wurttenberg and their importance to civil engineering. Bull. Int. Assoc .Eng. Geologist. (13): 45-49.

Orti Cabo, F. & Rosell Ortiz, L. 1981. Fábricas cristalinas de la anhidrita nodular y laminada. Acto Geológica Hispánica, tomo 16, n°4: 235 – 253.

Özgenoğlu, A. 1998. Intact rock classification based on time-dependent deformational properties. Int.J. of Rock Mech. & Min. Sci. Vol 35, 4-5: paper 016.

Sahores, J. 1962. Contribution a l'etude des phenomenes mécaniques accompagnant l'hidratation de l'ánhidrite. Thèse University Toulouse. Ver. Materiaux de Construction Pub. Tec. (126).

Steiner W. 1993. Swelling rock in tunnels: rock characterization, effect of horizontal stresses and construction Procedures. Int.J.Rock Mech. Min. Sci. & Geomech. Abstr., Vol 30. (4): 361-380.

EUROCK 2004 & 53rd Geomechanics Colloquium. Schubert (ed.) © 2004 VGE

Statistical evaluation of rock mass properties at TBM driving

Lucia IVANICOVA
Institute of Geotechnics, Slovak Academy of Sciences, Watsonova 45, Kosice, Slovak republic

ABSTRACT: The accurate and adequate input data obtained by engineering-geological investigation are necessary for appropriate evaluation of the rock environment. Results of common methods of engineering-geological investigation in real tunnelling conditions do not provide sufficient number of the measurement results for a proper use of statistical methods, and the results are only available with a certain time delay. This disadvantage may be eliminated by the inverse continuous method for rock mass properties determination (IKONA). The model rock mass strength obtained by this method continuously simulates the compressive strength changes in the tunnel face. The paper analyses the model strength by statistical methods for the purpose of rock mechanics knowledge specification The paper presents the results of the statistical evaluation of the Branisko rock mass properties, where the first motorway tunnel in Slovakia has been driven by the tunnel boring machine (TBM).

1 INTRODUCTION

The base of rock mechanics analysis is the geological database, which covers rock types, structural discontinuities and rock material properties. Proper rock environment assessment results require the precise and adequate input values obtained usually by engineering-geological investigation.

During full profile machine tunnelling there is a possibility to record and evaluate the tunnel driving process parameters affected by rock mass properties. This full-profile tunnelling process monitoring provides the observation of the rock properties changes on the tunnel face, thus complementing the engineering-geological investigation.

During the excavation of eastern part of the Branisko exploratory gallery, a unique computer monitoring and optimising system, called WORS, was installed on the Wirth TBII-330-H/M tunnelling machine. The principle of the WORS system has been developed at the Institute of Geotechnics, Slovak Academy of Sciences, and has been described in several works of Krupa (1998). In brief outline, the WORS system enables optimisation of the TBM operation by scanning the TBM parameters (applied thrust, torque, revolutions and position of cutterhead) with following real-time calculations of net advance rate, specific disintegration energy and recommended thrust. Driving with recommended thrust guarantees the excavation with minimum specific volume disintegration energy.

Another nonpareil project, developed at the Institute of Geotechnics, SAS, is the IKONA system. Using the investigation of the rock-tool interaction, a mathematical model of the interaction has been designed by Krupa (1998), giving opportunity for determination of rock mass